REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
15-10-2008	Annual Report	Nov. 2007 - Oct. 2008

4. TITLE AND SUBTITLE Multi-Input Multi-Output (MIMO) Radar - Diversity Means Superiority	**5a. CONTRACT NUMBER** N00014-07-1-0293
	5b. GRANT NUMBER N00014-07-1-0293
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Li, Jian	**5d. PROJECT NUMBER** 00064512
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Electrical and Computer Engineering P. O. Box 116130, University of Florida Gainesville, FL 32611	**8. PERFORMING ORGANIZATION REPORT NUMBER** N/A
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 North Randolph Street Arlington, VA 22203-1995	**10. SPONSOR/MONITOR'S ACRONYM(S)** ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) N/A

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

None

14. ABSTRACT

A multiple-input multiple-output (MIMO) radar system, unlike a standard phased-array radar, can transmit via its antennas linearly independent waveforms. An interesting current research topic on MIMO radar is the optimal design of the transmitted waveforms. We present a cyclic optimization algorithm for the synthesis of signal waveform matrix X whose covariance matrix R is equal or close to a previously optimized covariance matrix. As a MIMO radar can transmit different waveforms, reflected signals from scattering points will lack coherency, which facilitate the applications of adaptive array techniques. We also present a weighted least-squares based non-parametric and user parameter-free iterative adaptive approach (IAA), which can work with few snapshots (even one) under considerable noise, arbitrary array geometries, and uncorrelated as well as correlated sources. Although it is derived and analyzed under the passive array processing framework, IAA can also be applied to active sensing applications. Via simulated examples, we show the effectiveness of the proposed algorithms.

15. SUBJECT TERMS

Adaptive arrays, MIMO Radar, waveform diversity, waveform synthesis, cyclic optimization, array processing, passive sensing, active sensing, range-Doppler imaging, STAP, parameter estimation.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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MIMO Radar
- Diversity Means Superiority

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Annual report for the Office of Naval Research
Grant No. N00014-07-1-0293
November 2007 - October 2008

1. Summary

A multiple-input multiple-output (MIMO) radar uses multiple antennas to simultaneously transmit several linearly independent waveforms. It also uses multiple antennas to receive the reflected signals. It has been shown that by exploiting this waveform diversity, MIMO radar can overcome performance degradations caused by radar cross section (RCS) fluctuations, achieve flexible spatial transmit beampattern designs, provide high-resolution spatial spectral estimates, and significantly improve the parameter identifiability. The MIMO radar can be grouped into two classes according to their antenna configurations. One class is the conventional radar array, in which both the transmitting and receiving antennas are closely spaced for coherent transmission and detection. The other class is the diverse antenna configuration, where the antennas are separated far away from each other to achieve spatial diversity gain.

The waveform diversity offered by MIMO radar is the main reason for its superiority over standard phased-array radar, which transmits scaled versions of a single waveform. For colocated transmit and receive antennas, for example, MIMO radar has been shown to have the following appealing features: higher resolution, superior moving target detection ability, better parameter identifiability, and direct applicability of adaptive array techniques; in addition, the covariance matrix of the probing signal vector transmitted by a MIMO radar system can be designed to approximate a desired transmit pattern – an operation that, once again, would be hardly possible for conventional phased-array radar. An interesting current research topic in this area of MIMO radar system is the optimal synthesis of the transmitted waveforms. Optimization of a performance metric directly with respect to the signal matrix can lead to an intractable problem even under a relatively simple low peak-to-average-power ratio (PAR) constraint. For this reason, we proposed the following strategy: first optimize the performance metric of interest with respect to the signal covariance matrix $\mathbf{R}$; and then synthesize a signal waveform matrix that, under low PAR constraint, realize (at least approximately) the optimal covariance matrix derived in the first step. We presented a cyclic optimization algorithm for the synthesis of a signal waveform matrix to (approximately) realize a given covariance matrix $\mathbf{R}$, under the constant modulus constraints or low PAR constraint. The output of the cyclic algorithm can be used to obtain either a waveform matrix whose covariance matrix is exactly equal to $\mathbf{R}$ but whose PAR is slightly larger than the imposed value, or a waveform matrix with the imposed PAR but whose covariance matrix may differ slightly from $\mathbf{R}$ – the type of application will dictate which one of these two kinds of waveforms will be more useful.

As a MIMO radar can transmit different waveforms, reflected signals from scattering points will lack coherency, which facilitates the application of adaptive array techniques. When the array steering vectors are accurately known, existing approaches, such as Capon and APES, have been shown to offer

increased resolution and better interference rejection. However, when high levels of noise or model errors are present, the performance of these existing adaptive approaches can degrade significantly. Recently, a weighted least-squares based non-parametric and user parameter-free iterative adaptive approach (IAA) was proposed in array processing and other sensing applications. IAA can work with few snapshots (even one) under considerable noise, arbitrary array geometries, and uncorrelated as well as correlated sources. The Bayesian information criterion (BIC) can be used to sparsify the IAA estimates. Further improvements in performance can be achieved by employing the last step of the parametric RELAX algorithm initiated by the estimates of IAA with BIC. The RELAX extension also allows IAA to estimate off-grid sources more accurately. Although IAA is derived and analyzed under the passive array processing framework, it can also be applied to active sensing applications, such as single-input single-output (SISO) radar range-Doppler imaging, and space-time adaptive processing (STAP), due to the similarities of the underlying data models. We showed via simulations that IAA outperforms the most competitive methods in the literature in the corresponding application areas. It is important to note that IAA can be applied to all discussed application areas without any essential modifications. IAA appears to be a viable candidate for practical applications as it does not require any user parameter, has a simple formulation, provides superresolution, facilitates parallel processing and shows good performance and robustness.

2. Selected Paper Abstracts

T. Yardibi, J. Li, W. Roberts, and P. Stoica, "An Iterative Adaptive Approach for Passive or Active Array Processing", *Journal of the Franklin Institute*, submitted.

In this paper we present a non-parametric, user parameter-free, weighted least squares-based iterative adaptive approach (IAA) for passive or active sensing applications. We derive IAA under the passive array processing framework and show that it can be used in single-input single-output (SISO) radar range-Doppler imaging and multiple-input multiple-output (MIMO) synthetic aperture radar (SAR) imaging as well as in space time adaptive processing (STAP) without requiring any secondary data or training. An approach to regularize IAA is presented and IAA is extended to give point source estimates by the use of a model-order selection tool, the Bayesian information criterion (BIC). Moreover, it is shown that further improvements in resolution and accuracy can be achieved by applying the parametric RELAX algorithm to refine the IAA with BIC estimates. The performance of IAA is evaluated for all the aforementioned application areas and it is shown that IAA outperforms the existing approaches in the literature.

P. Stoica, J. Li, and X. Zhu, "Waveform Synthesis for Diversity-Based Transmit Beampattern Design," *IEEE Transactions on Signal Processing*, Vol. 56, No. 6, pp. 2593-2598, June 2008.

Transmit beampattern design is a critically important task in many fields including defense and homeland security as well as biomedical applications. Flexible transmit

beampattern designs can be achieved by exploiting the waveform diversity offered by an array of sensors that transmit probing signals chosen at will. Unlike a standard phased-array, which transmits scaled versions of a single waveform, a waveform diversity based system offers the flexibility of choosing how the different probing signals are correlated with one another. Recently proposed techniques for waveform diversity-based transmit beampattern design have focused n the optimization of the covariance matrix **R** of the waveforms, as optimizing a performance metric directly with respect to the waveform matrix is a more complicated operation. Given an **R**, obtained in a previous optimization stage or simply pre-specified, the problem becomes that of determining a signal waveform matrix **X** whose covariance matrix is equal or close to **R**, and which also satisfies some practically motivated constraints (such as constant-modulus or low peak-to-average-power ratio constraints). We propose a cyclic optimization algorithm for the synthesis of such an **X**, which (approximately) realizes a given optimal covariance matrix **R** under various practical constrains. A numerical example is presented to demonstrate the effectiveness of the proposed algorithm.

J. Li, L. Xu, P. Stoica, D. Bliss, and K. Forsythe, "Range Compression and Waveform Optimization for MIMO Radar – A Cramer-Rao Bound Based Study," *IEEE Transactions on Signal Processing*, Vol. 56, No. 1, pp. 218-232, January 2008.

A multi-input multi-output (MIMO) radar system, unlike standard phased-array radar, can transmit via its antennas multiple probing signals that may be correlated or uncorrelated with each other. This waveform diversity offered by MIMO radar enables superior capabilities compared with a standard phased-array radar. One of the common practices in radar has been range compression. We first address the question of "to compress or not to compress" by considering both the Cramér-Rao bound (CRB) and the sufficient statistic for parameter estimation. Next, we consider MIMO radar waveform optimization for parameter estimation for the general case of multiple targets in the presence of spatially colored interference and noise. We optimize the probing signal vector of a MIMO radar system by considering several design criteria, including minimizing the trace, determinant, and the largest eigenvalue of the CRB matrix. We also consider waveform optimization by minimizing the CRB of one of the target angles only or one of the target amplitudes only. Numerical examples are provided to demonstrate the effectiveness of the approaches we consider herein.

X. Tan, W. Roberts, J. Li, and P. Stoica, "Range-Doppler Imaging Via a Train of Probing Pulses," *IEEE Transactions on Signal Processing*, submitted.

We consider range-Doppler imaging via transmitting a train of probing pulses. We present two methods for range-Doppler imaging. The first one is based on the instrumental variables (IV) filter and the second one is based on the iterative adaptive approach (IAA). Numerical results show that both methods can suppress interference from neighboring range and Doppler bins. An attractive feature of the IV filter is that it can be computed offline. IAA has better performance than IV and has super resolution, but at the cost of a higher computational complexity.

J. Li, P. Stoica, and X. Zhu, "MIMO Radar Waveform Synthesis," *2008 IEEE Radar Conference*, Rome, Italy, May 2008, invited.

A multi-input multi-output (MIMO) radar system, unlike a standard phased-array radar, can transmit multiple probing signals that are correlated or uncorrelated with each other. This waveform diversity offered by the MIMO radar is the main reason for its superiority over the standard phased-array radar. An interesting current research topic in MIMO radar is the optimal synthesis of the transmitted waveforms. Recently proposed techniques for MIMO radar waveform synthesis have focused on the optimization of the covariance matrix **R** of the waveforms, as optimizing a performance metric directly with respect to the waveform matrix is a more complicated operation. Given an **R**, the problem becomes that of determining a signal waveform matrix **X** whose covariance matrix is equal or close to **R**, and which also satisfies some practically motivated constraints. We propose a cyclic optimization algorithm for the synthesis of such an **X**, which (approximately) realized a given optimal covariance matrix **R** under various practical constraints, and which also has good auto- and cross-correlation properties in time, if desired. A number of numerical examples are presented to demonstrate the effectiveness of the proposed algorithm.

J. Li, X. Zhu, P. Stoica, and M. Rangaswamy, "Iterative Space-Time Adaptive Processing", *2009 IEEE Digital Signal Processing Workshop*, Marco Island, FL, January 2009, invited.

To reduce the need of secondary data and/or accurate prior knowledge of the clutter statistics in space-time adaptive processing (STAP), we present herein a user parameter-free and secondary data-free fully automatic weighted least squares based iterative adaptive approach (IAA) to angle-Doppler imaging for airborne surveillance radar systems.

3. Awards

The Second Place Best Student Paper Award at the 41st Asilomar Conference on Signals, Systems and Computer in Pacific Grove, California, for the paper:
X. Zhu, J. Li, P. Stoica, and J. R. Guerci, "Knowledge-Aided Space-Time Adaptive Processing", *41st Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, November, 2007.

4. Students

Xumin Zhu (graduated with Ph.D.), Xing Tan, Duc Vu (new), Arsen Ivanov (new), William Roberts (SMART Fellowship).